Measurement of $\Xi^- \rightarrow \Lambda\pi^-$ and $\Omega^- \rightarrow \Lambda K^-$ Decay Parameters

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Based on 144 million polarized $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow p\pi^-$ and 5.5 million unpolarized $\Omega^- \rightarrow \Lambda K^-$, $\Lambda \rightarrow p\pi^-$ decays, the HyperCP collaboration at Fermilab has measured the decay parameters β_{Ξ^-}, γ_{Ξ^-}, and α_{Ω^-}. Our results indicate that β_{Ξ^-} and α_{Ω^-} are small, but nonzero. Implications of the β_{Ξ^-} measurement on the $\Lambda\pi^-$ phase-shift difference will be discussed. The nonzero value of α_{Ω^-} is the first unambiguous evidence of parity violation in Ω^- decays. A preliminary measurement of $\alpha_{\overline{\Omega}^+}$ will also be presented, based on 1.9 million $\overline{\Omega}^+ \rightarrow \overline{\Lambda}K^+$, $\overline{\Lambda} \rightarrow \overline{p}\pi^+$ events. The comparison of α_{Ω^-} and $\alpha_{\overline{\Omega}^+}$ provides a test of CP invariance for Ω decays.

1. Introduction

A nonleptonic hyperon decay $B_i \rightarrow B_f\ X$, where B and X represent a spin-half baryon and a spin-zero meson respectively, is described by the following three decay parameters,

$$\alpha = \frac{2Re(A^*_{J-\frac{1}{2}}A_{J+\frac{1}{2}})}{|A_{J-\frac{1}{2}}|^2 + |A_{J+\frac{1}{2}}|^2}, \quad \beta = \frac{2Im(A^*_{J-\frac{1}{2}}A_{J+\frac{1}{2}})}{|A_{J-\frac{1}{2}}|^2 + |A_{J+\frac{1}{2}}|^2}, \quad \gamma = \frac{|A_{J-\frac{1}{2}}|^2 - |A_{J+\frac{1}{2}}|^2}{|A_{J-\frac{1}{2}}|^2 + |A_{J+\frac{1}{2}}|^2}, \tag{1}$$

where J is the spin of the parent hyperon.

For $J = \frac{1}{2}(J = \frac{3}{2})$, $A_{J-\frac{1}{2}}$ and $A_{J+\frac{1}{2}}$ are amplitudes of S-wave(P-wave) and P-wave(D-wave), and correspond to parity-violating(parity-conserving) and parity-conserving(parity-violating) states respectively. Hence, for $\Xi \rightarrow \Lambda\pi$ decays,

$$\alpha_\Xi = \frac{2Re(S^*P)}{|S|^2 + |P|^2}, \quad \beta_\Xi = \frac{2Im(S^*P)}{|S|^2 + |P|^2}, \quad \gamma_\Xi = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}; \tag{2}$$

and for the decays of $\Lambda \rightarrow p\pi$ and $\Omega \rightarrow \Lambda K$, $\alpha_\Lambda = \dfrac{2Re(S^*P)}{|S|^2 + |P|^2}$, $\alpha_\Omega = \dfrac{2Re(P^*D)}{|P|^2 + |D|^2}$.

Experimentally, CP violation in hyperon decays can be measured via the asymmetry defined as the difference of the α decay parameters between hyperon and antihyperon decays for instance, $A_\Xi = \dfrac{\alpha_\Xi + \alpha_{\overline{\Xi}}}{\alpha_\Xi - \alpha_{\overline{\Xi}}}$, for the $\Xi \rightarrow \Lambda\pi$ decays.

Theoretically, the asymmetry A_Ξ can be obtained through a model-independent approximation [1], $A_\Xi = -\tan(\delta_p - \delta_s)\sin(\phi_p - \phi_s)$, in which $\delta_p - \delta_s$ is the strong-interaction phase-shift difference between the p-wave and s-wave of the $\Lambda\pi$ system, and $\phi_p - \phi_s$ is the CP-violating weak-interaction phase-shift difference in the decay. The weak phase-shift

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difference has been determined on theory [1,2], while the strong phase-shift difference is still ambiguous. Theoretical predictions of $\delta_p - \delta_s$ vary from $-4.2°$ to $16°$ based on different models [3]-[9]. The calculations from chiral perturbation theory tend to give negative values [4]-[8]. Noticing if *CP*-violating weak phases are negligible, $\delta_p - \delta_s$ can be determined through $\frac{\beta_\Xi}{\alpha_\Xi} = \tan(\delta_p - \delta_s)$. Hence measuring β_Ξ and α_Ξ is equivalent to measuring $\delta_p - \delta_s$, which will provide a reference to test different theoretical models.

In $\Omega \to \Lambda K$ decays, theoretically, D-wave is kinematically suppressed and α_Ω is expected to be nearly zero [10]. Non-zero α_Ω indicates parity violation in this decay. Previous experimental results [11]-[13], which were measured by about ten thousand or even fewer Ω events, as well as the PDG value of α_Ω [14], are consistent with zero within a few percent of the statistical error. With several million Ω decays collected by *HyperCP* experiment at Fermilab, the statistical error of the α_Ω measurement will be significantly reduced.

2. Analysis Method

To measure β_Ξ and γ_Ξ, we use polarized $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ decays, where the angular distribution of the joint decay has the form $\frac{d^2N}{d\Omega_\Lambda d\Omega_p} = \frac{1}{(4\pi)^2}(1+\alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda})(1+\alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p})$. $\vec{P}_\Xi$ and $\vec{P}_\Lambda$ are the polarizations of Ξ and Λ, $\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{\Lambda})\hat{\Lambda} + \beta_\Xi(\vec{P}_\Xi \times \hat{\Lambda}) + \gamma_\Xi \hat{\Lambda} \times (\vec{P}_\Xi \times \hat{\Lambda})}{1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}}$.

In the coordinate system defined as $\hat{z}' = \hat{\Lambda}$, $\hat{x}' = \frac{\vec{P}_\Xi \times \hat{\Lambda}}{|\vec{P}_\Xi \times \hat{\Lambda}|}$, $\hat{y}' = \hat{z}' \times \hat{x}'$, the proton angular distribution can be separated in terms of α_Ξ, β_Ξ, and γ_Ξ as followings:

$$\frac{d^2N}{d\Omega_\Lambda d\cos\theta_{pz'}} = \frac{1}{8\pi}\left[(1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}) + \alpha_\Lambda(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{\Lambda})\cos\theta_{pz'}\right], \tag{3}$$

$$\frac{dN}{d\cos\theta_{px'}} = \frac{1}{2}(1 + \frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi \cos\theta_{px'}), \tag{4}$$

$$\frac{dN}{d\cos\theta_{py'}} = \frac{1}{2}(1 + \frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi \cos\theta_{py'}), \tag{5}$$

where $\cos\theta_{pz'} = \hat{p} \cdot \hat{z}'$, $\cos\theta_{px'} = \hat{p} \cdot \hat{x}'$, $\cos\theta_{py'} = \hat{p} \cdot \hat{y}'$. Given α_Ξ and α_Λ, $\vec{P}_\Xi$ can be measured by Eq. (3). Since $\alpha_\Xi^2 + \beta_\Xi^2 + \gamma_\Xi^2 = 1$, instead of using ($\alpha_\Xi$,$\beta_\Xi$,$\gamma_\Xi$), ($\phi_\Xi$,$\beta_\Xi$,$\gamma_\Xi$) is alternatively used to describe $\Xi^- \to \Lambda\pi^-$ decays,

$$\beta_\Xi = \sqrt{1 - \alpha_\Xi^2}\sin\phi_\Xi, \quad \gamma_\Xi = \sqrt{1 - \alpha_\Xi^2}\cos\phi_\Xi. \tag{6}$$

The ratio of the slopes of Eq. (4) and Eq. (5), $S_x \equiv \frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi$ and $S_y \equiv \frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi$, gives us

$$\tan\phi_\Xi = \frac{\beta_\Xi}{\gamma_\Xi} = \frac{S_x}{S_y}. \tag{7}$$

Using Eq. (6), we get β_Ξ and γ_Ξ after ϕ_Ξ is measured by Eq. (7).

For $\Omega \to \Lambda K \to p\pi K$ decays, the proton angular distributions with respect to $\hat{z}'$, $\hat{x}'$, and $\hat{y}'$ in Λ rest frame have the same form as those of the Ξ, except that those with respect to $\hat{x}'$ and $\hat{y}'$ have additional tensor polarization terms because $J = \frac{3}{2}$ [12,16]. As we only measure α_Ω, we use unpolarized $\Omega \to \Lambda K$ events. Hence the terms associated with β_Ω and γ_Ω vanish, and the proton angular distribution is simplified as

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega\alpha_\Lambda \cdot \cos\theta), \tag{8}$$

where θ is the polar angle of proton in the Λ helicity frame.

Hybrid Monte-Carlo method (HMC) [17] is applied to correct the acceptance in our data analysis. We take all variables from each real event except $\cos\theta$ to generate Hybrid Monte-Carlo (HMC) events with uniform $\cos\theta$, and then let all the HMC events go through the software spectrometer, triggers, event selection cuts to simulate the real events. Assuming the Monte-Carlo code describes the spectrometer perfectly, the distortion of the proton angular distribution of HMC events by the acceptance should be exactly the same as for real events. Matching the HMC event $\cos\theta$ distribution to the real event $\cos\theta$ distribution gives us S_x, S_y and hence ϕ_Ξ, β_Ξ and γ_Ξ for $\Xi^- \to \Lambda\pi^-$ decays, and $\alpha_\Omega\alpha_\Lambda$ for $\Omega^- \to \Lambda K^-$ decays.

To verify the analyis codes, we generated Monte-Carlo samples with different input values of $\vec{P}_\Xi$, β_Ξ, γ_Ξ, and $\alpha_\Omega\alpha_\Lambda$. Then we analyzed these Monte-Carlo samples with HMC to obtain the measurement values of $\vec{P}_\Xi$, β_Ξ, γ_Ξ, and $\alpha_\Omega\alpha_\Lambda$. The differences between the measured values and input values being zero indicate that the analysis codes work properly.

3. Results

3.1. Decay Parameters of $\Xi^- \to \Lambda\pi^-$

About 144 million -3 mrad and $+3$ mrad events of polarized Ξ^- decays are used for the measurement. The proton $\cos\theta_{px'}$ and $\cos\theta_{py'}$ distributions for data and HMC after weighted are shown in Fig. 1.

Table 1
The measured slopes S_x, S_y, and ϕ_Ξ angles.

p_Ξ (GeV/c)	S_x	S_y	ϕ_Ξ (degree)
139	-0.00037 ± 0.00047	0.01191 ± 0.00041	-1.77 ± 2.28
152	-0.00046 ± 0.00047	0.01447 ± 0.00038	-1.81 ± 1.88
162	-0.00038 ± 0.00041	0.01557 ± 0.00035	-1.39 ± 1.49
173	-0.00074 ± 0.00040	0.01880 ± 0.00036	-2.26 ± 1.22
191	-0.00123 ± 0.00040	0.02109 ± 0.00040	-3.33 ± 1.08
Average			-2.39 ± 0.64

The measurements of slopes S_x and S_y in five Ξ momentum bins and the associated ϕ

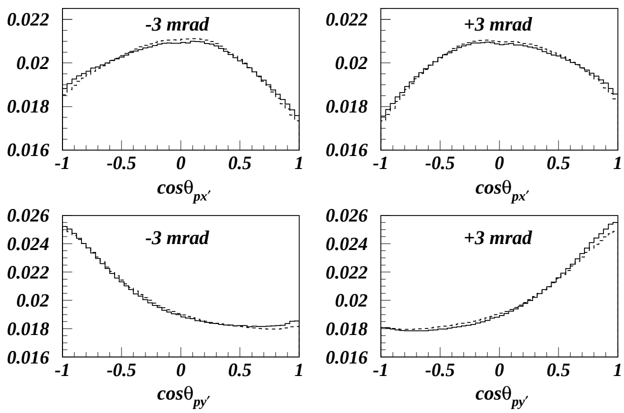

Figure 1. The weighted $\cos\theta_{px'}$ and $\cos\theta_{py'}$ distributions for data (solided) and HMC (dashed).

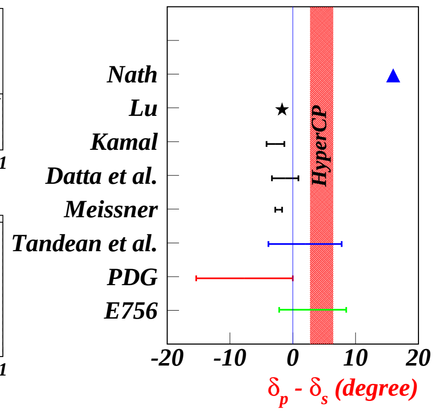

Figure 2. The comparison with other experimental results and theoretical predictions.

angles are shown in Table 1. Using $\alpha_\Xi = -0.458 \pm 0.012$ [14] from PDG and Eq. (6), we obtain

$$\beta_\Xi = -0.037 \pm 0.011 \text{ (stat)} \pm 0.010 \text{ (syst)}, \tag{9}$$

$$\gamma_\Xi = 0.888 \pm 0.0004 \text{ (stat)} \pm 0.006 \text{ (syst)} \tag{10}$$

$$\delta_p - \delta_s = \tan^{-1}\left(\frac{\beta_\Xi}{\alpha_\Xi}\right) = [4.6 \pm 1.4 \text{ (stat)} \pm 1.2 \text{ (syst)}]^\circ \tag{11}$$

As shown in Fig. 2, our result is consistent with E756's measurement but is inconsistent with the Chiral perturbation predictions [4]-[8]. $\delta_p - \delta_s$ is about a factor of 0.6 relative to the one of $p\pi$ scattering, which indicates CPV in $\Xi \to \Lambda\pi$ is smaller than that in $\Lambda \to p\pi$ but it is not negligible. The results of this analysis has been published on [19].

3.2. Decay Parameter of $\Omega^- \to \Lambda K^-$

After all event selection cuts, 4.5 million events from 1999 run (RUN-II) and 1.0 million events from 1997 run (RUN-I) of $\Omega^- \to \Lambda K^-$ decay were used to measure α_Ω.

Fig. 3 shows the difference of $\cos\theta$ distributions between real and HMC events before and after the weighting for the analysis on 1999 data. The slope of proton angular distribution S_m for 1999 run was measured to be $S_m = (1.16 \pm 0.12) \times 10^{-2}$ with χ^2 being 23 for 19 degrees of freedom. The background contribution, S_b, was measured from mass sidebands, $S_b = (7.17 \pm 3.04) \times 10^{-2}$. Using $\alpha_\Omega \alpha_\Lambda = \frac{N_m}{N_s} S_m - \frac{N_b}{N_s} S_b$ to perform the background subtraction (N_m, N_s, and N_b correspond to the numbers of observed, signal, and background events). The systematic error study for 1999 data is found to be 0.10×10^{-2}, and the systematic error study for 1997 data is still undergoing. Finally, our results are:

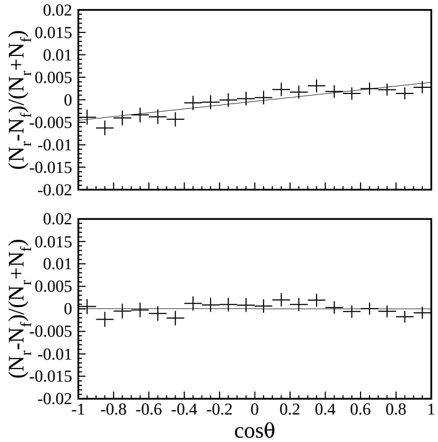

Figure 3. The difference of $\cos\theta$ distribution between real and HMC events. Top: before weighted. Bottom: after weighted.

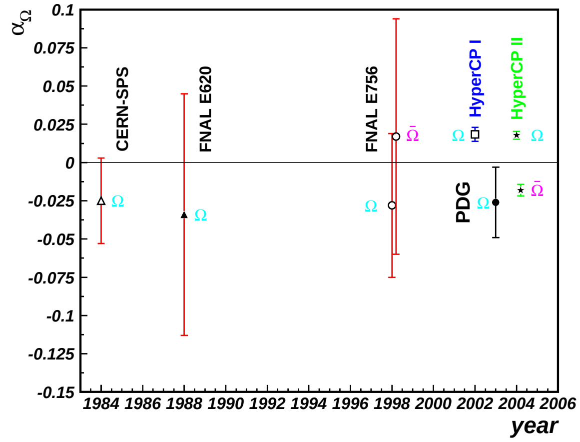

Figure 4. Comparison with other results.

$$\alpha_\Omega\alpha_\Lambda = [1.18\pm0.29(\mathrm{stat})] \times 10^{-2}(1997\ \mathrm{Run}), \tag{12}$$

$$\alpha_\Omega\alpha_\Lambda = [1.14\pm0.12(\mathrm{stat})\pm0.10(\mathrm{syst})]\times10^{-2}(1999\ \mathrm{Run}). \tag{13}$$

Using PDG value $\alpha_\Lambda = 0.642 \pm 0.013$ [14], we get

$$\alpha_\Omega = [1.84\pm0.46(\mathrm{stat})] \times 10^{-2}(1997\ \mathrm{Run}), \tag{14}$$

$$\alpha_\Omega = [1.78\pm0.19(\mathrm{stat})\pm0.16(\mathrm{syst})]\times10^{-2}(1999\ \mathrm{Run}). \tag{15}$$

Using the same code and event selection cuts, we have analyzed 1.9 million $\bar{\Omega}^+ \to \bar{\Lambda}K^+$, $\bar{\Lambda} \to \bar{p}\pi^+$ events. The preliminary results of $\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}$ and $\alpha_{\overline{\Omega}}$ are followings:

$$\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}} = [1.16\pm0.18(\mathrm{stat})]\times10^{-2}, \quad \alpha_{\overline{\Omega}} = [-1.81\pm0.28(\mathrm{stat})]\times10^{-2}. \tag{16}$$

Using the measured values of $\alpha_\Omega\alpha_\Lambda$ and $\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}$, asymmetries are determined to be

$$\delta_{\Omega\Lambda} \equiv \alpha_\Omega\alpha_\Lambda - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}} = [-0.02 \pm 0.22(\mathrm{stat})]\times10^{-2}, \tag{17}$$

and

$$A_{\Omega\Lambda} \equiv \frac{\alpha_\Omega\alpha_\Lambda - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}}{\alpha_\Omega\alpha_\Lambda + \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}} = [-0.87 \pm 9.41(\mathrm{stat})]\times10^{-2}. \tag{18}$$

The comparison of the HyperCP measurement of α decay parameter with other experimental results is shown in Fig. 4. Theoretical predictions of $A_{\Omega\Lambda}$ by Tandean [18] using the standard model (*SM*) and chromomagnetic-penguin operators which includes possible physics beyond the standard model (*CMO*) are $\leq 4\times10^{-5}$ and $\leq 8\times10^{-3}$ respectively. Our result is consistent with zero within the statistical error. However, in order to find whether $\Omega \to \Lambda K \to p\pi K$ decays are involved in physics beyond the standard model, at least a hundred times of the current statistics is required.

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